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BY

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THE BURNING OF FOREST FUELS AND AIR QUALITY

I. Introduction

In the Pacific Northwest like in many other parts of the country, burning is the standard method for disposing of undesirable waste including logging debris and agriculture residue. About two hundred thousand acres of logging slash are burned annually west of the Cascades in the States of Washington and Oregon. In addition two hundred and fifty thousand acres of grasslands are burned in Oregon. Many other forms of residue are also disposed of by burning.

Burning of waste contributes unknown quantities of gases particulate to the atmosphere which may result in local or area wide pollution. Burning appears to be the most practical and economical way of disposal. In the future it is hoped that more complete utilization will elminate the necessity of burning. But until then prescribed burning may be the only way to reduce the fire hazard and thereby reduce the possibility of sustained pollution of natural fires occurring during periods of limited ventilation or low inversions.

Contribution of burning of agriculture waste to air pollution has been studied in California by McElroy (1959), Bell and Waggoner (1961), Feldstein et al (1963) and Darley et al (1966). Limited information has been available on the contribution of slash disposal to air pollution. Feldstein et al (1963) states the general rule that the higher the combustion temperature and the longer the residence time at that temperature the more complete the combustion will be if enough oxygen is present. They present data from single and multiple

chamber incinerators which support the rule of thumb. However local pollution is a function of incomplete combustion, total amount of material consumed and completeness of dispersion. Furthermore the primary objective of slash burning is not complete combustion but to 1) expose mineral soil for regeneration, 2) reduce fire hazard, and 3) reduce undesirable species. Since fire hazard is directly related to the amount and percentage of fine fuels present, the objectives of slash disposal and minimum pollution may be achieved by a hot fire of sufficient duration to consume the fine fuels under favorable condtions for atmospheric dispersal. The hot fire, under field conditions, will provide the additional buoyant lift necessary for dispersion.

The purpose of this paper is to present a summary of the combustion products resulting from burning of Douglas-fir slash under field conditions. More detailed results are presented elsewhere (Fritschen et al 1969).

II. Experimental Procedures

A. Experimental site.

The experimental site was located on Charles Lathrop Pack Experimental Forest of the University of Washington, 45 miles southeast of Tacoma, Figure 1. Vegetation on the site regenerated naturally following a forest fire in the 1920's and consists of Douglas-fir with Bracken fern, salal, trailing blackberry, hot clover, geranium and other herbs and shrubs. During the spring and summer of 1967, 30 acres of Douglas-fir and associated species were clearcut. Approximately 18 acres of this area was burned in a broadcast burn during the early spring of 1968.

B. Analytical methods

Gas samples. Samples of air were obtained using evacuated bottles and the water displacement method (Pickford et al, 1969). The evacuated

containers were used to obtain samples from the flame area in the broadcast burn and from the smoke plume with an instrumented aircraft. Air samples downwind from the broadcast burn were obtained by the water displacement method.

All samples were analyzed for carbon monoxide with a Beckman infrared analyzer, Model 315 and for CO_2 with a Beckman infrared analyzer, Model 215. When the carbon monoxide and carbon dioxide concentrations were off scale of the analyzer the samples were diluted with dry nitrogen using standard techniques. In addition selected samples were passed through a freeze-out trap and were analyzed with a gas chromatograph and a mass spectrometer.

To provide a check, air was passed through a charcoal filter and subjected to analysis with the gas chromatograph and mass spectrometer.

Particulate. High volume samplers were used to obtain particulate samples on the ground. The total amount of particulate in the smoke plume was determined with an airborne version of the integrating nephelometer (Alquist and Charlson, 1968).

III. Results and Discussion

A. Gas Analysis

Location of ground sampling sites are shown in Figure 2. The results of carbon monoxide and carbon dioxide analysis of gas samples collected from ground sampling sites are shown in Table 1. From these data two types of fire can be characterized. Hot fire about 850°C with complete combustion and cold fire about 500°C with incomplete combustion. These are illustrated by the analysis of gases sampled directly from the fire area. They show a CO/CO_2 of 0.029 from the hot fire and about 0.20 from the cold fire.

From meteorological observations, photography and other sources the fire was characterized by three stages. The stage after ignition when a strong convection column was established, the die-down stage during

TABLE 1. Carbon monoxide and carbon dioxide concentrations obtained from the flame area and sample net during a broadcast burn on Pack Forest, La Grande, Washington, June 25, 1968

Location and time	Carbon Monoxide Average	Carbon Monoxide s.d.[1/]	Carbon dioxide Average	Carbon dioxide s.d.[1/]	$\frac{CO}{CO_2}$	$\frac{CO}{CO_2-330}$ [2/]
	ppm	ppm	ppm	ppm		
1300-1340						
Line 1	8.1	3.2	561	97		0.039
Line 2	5.2	3.8	620	251		0.024
Line 3	5.2	2.6	480	37		0.035
Average	6.5	3.4	555	149		0.034
1430-1630						
Line 1	18.7	10.3	626	154		0.072
Line 2	10.0	3.3	665	232		0.036
Line 3	6.8	1.1	575	127		0.033
Average	13.8	9.7	625	164		0.054
1630-1830						
Line 1	6.5	2.8	530	118		0.045
Line 2	7.6	0.6	519	93		0.048
Line 3	5.6	3.8	596	188		0.066
Average	6.6	2.7	543	129		0.051
Flame gas						
850°C	917		31,000		0.029	
500°C	4,315		22,000		0.194	
500°C	8,104		40,000		0.203	

1/ s.d., Standard Deviation.

2/ Ambient CO_2 assumed to be 330 ppm.

which the rate of energy release was less than the first stage and the convection column could not maintain itself against the ambient winds, and

the stage when the fire has disintegrated into many local bonfires or hotspots. These three stages are roughly characterized by the sampling periods shown in Table 1. That is, stage I refers to the period from 1300 to 1340; stage II, from 1430 to 1630, and stage III, from 1630 to 1830.

The CO and CO_2 concentrations during the three stages are shown in Figures 3, 4, and 5. During stage I, as a result of convergence and turbulent mixing, column, the CO and CO_2 concentration was low and decreased rapidly downwind from the fire, that is, the concentration in line 1 is greater than in line 2 and 3 (Figure 3). The second stage of fire is represented by Figure 4 as having high concentrations of CO. High concentration of the CO indicates more incomplete combustion. Concentrations of CO and CO_2 during the third stage were similar to the first stage (Figure 5). The fire had degenerated into individual hot spots with sufficient mixing to promote nearly complete combustion.

The ratios of $CO/(CO_2 - 330)$ in the sampling net, Table 1, can be compared directly to the CO/CO_2 ratios of the flame gases. The average ratio in sampling net was 0.034 during stage I, 0.054 during stage II, and 0.051 during stage III. These ratios are similar to the ratio obtained from 850°C flame gas.

Rapid dilution of CO and CO_2 is shown from the fire to and through the sampling network. Using the fire concentrations for CO and CO_2, the dilution from the fire to the sampling net ranges from 100 to 800 for CO and from 40 to 80 for CO_2. These results suggest that a portion of the CO is being oxidized before reaching the sampling net while the CO_2 is just being diluted. Within the sampling net, CO diluted 1.8 times from line 1 to line 3. CO_2 diluted 1.6 times over the same distance.

Infrared spectophotometer analysis of gas samples collected from the fire area and from the plume at 4,500 feet are shown in Table 2.

TABLE 2. Infrared spectrophotometer analyses of smoke samples June 25, 1968 broadcast fire at Pack Forest.

Component	PB-1[1/]	PB-3[2/]	G-11[3/]	G-4[4/]	G-2[4/]
	ppm	ppm	ppm	ppm	ppm
Carbon dioxide	490	820	580	330	320
Carbon monoxide	24	58	40	0	0
Methane	4	10	5	2	2
Ethylene	1	1	1	0	0

1/ PB-1, Period 2 (see Fig. 2 for location)

2/ PB-3, Period 2 (See Fig. 2 for location)

3/ G-11, Period 2 (See Fig. 2 for location)

4/ G-2, G-4 collected from smoke plume with airplane.

Sample PB-1, PB-3 and G-11 were taken as close to the fire as a man could walk without a fire suit. These samples contain from 4 to 10 ppm methane and 1 ppm ethylene in addition to CO and CO_2. Samples G-2 and G-4 were taken with the airplane and show only background levels of methane. Both CO and CO_2 had diluted to ambient levels at this elevation.

Results of more detailed analysis of gas samples by a combined gas chromatograph-mass spectrometer technique are shown in Table 3. In general the concentrations of all of the compounds are low. The most significant components appear to be the low molecular weight hydrocarbons and alcohols including ethylene, ethane, propene, propane, methanol and ethanol. Acetone and the aromatic compounds, benzene and toluene

TABLE 3. Combined gas chromatograph-mass spectrometer analysis of smoke samples from June 25, 1968 broadcast burn, Pack Forest.

Component	Activated Charcoal	Sample location						
		A-3[1]	I-1[2]	E-1[3]	PB-1[4]	G-11[4]	G-4[5]	G-2[5]
	ppm							
Ethylene	.03	.07	.05	.01	.99	1.05	.04	.09
Ethane	.01	.02	.02	.00	.50	1.24	.02	.05
Carbonyl sulfide	.00	1.00	.50	.50	.00	.00	.00	.00
Propene	.13	.02	.01	.00	.34	.70	.60	.01
Propane	.09	.01	.01	.00	.21	.60	.01	.02
Methanol	.00	3.07	1.92	1.60	1.03	2.86	.45	.34
Freon 12	.01	.00	.90	.00	.00	.00	.00	.00
Acetaldehyde	.00	.04	.02	.03	.00	.00	.00	.00
Isobutane	.01	.00	.21	.00	.00	.00	.00	.00
1-Butene	.16	.05	.00	.08	.00	.00	.00	.00
Ethanol	.00	.18	.26	.06	.14	.10	.06	.15
Furan	.04	.00	.00	.00	.12	.45	.00	.00
Acetone	.00	.01	.05	.01	.24	.37	.02	.23
Dichloromethane	.01	.65	.48	.11	.00	.00	.00	.00
Dichloroethylene	.01	.00	.00	.00	.00	.00	.00	.00
N-Pentane	.01	.00	.04	.01	.00	.00	.00	.00
2-Pentene	.00	.02	.02	.00	.00	.00	.00	.00
2-Methyl Furan	.00	.02	.02	.00	.00	.00	.00	.00
Ethyl Acetate	.00	.00	.00	.00	.03	.17	.00	.00
Benzene	.07	.04	.03	.03	.09	1.79	.00	.01
2,4-Dimethyl 2-Pentene	.00	.02	.02	.00	.00	.00	.00	.00
N-Heptane	.00	.00	.00	.00	.01	.72	.01	.01
1,1,2 Trichloroethane	.00	3.42	.44	.21	.00	.00	.00	.00
Toluene	.01	.07	.40	.03	.11	.09	.04	.02
Xylene	.00	.04	.07	.00	.00	.00	.00	.00

1/ A-3 taken during Period 3
2/ I-1 taken during Period 2
3/ E-1 taken during Period 3
4/ See Fig. 4 for location of PB-1 and G-11
5/ See Fig. 1 for location of G-4 and G-2

appear in most of the samples. Several unsaturated compounds in addition to ethylene and propene were identified but the quantities were relatively low.

The activated charcoal results represents a much larger sample of air than the bag or the tank samples. Because of this many compounds were detected which could not be seen in the smaller samples. Only compounds with concentrations of 0.01 ppm or greater are included in Table 3 because of the uncertainties in identifcation at lower levels, and also the increased likelihood of seeing background contaminants instead of compounds from the burn.

A number of compounds were detected that are known to have been or suspected to have been introduced accidentally. Freon 12 for example was found in samples near the nephelometer which employes this gas in its operation. Carbonyl sulfide was found only in the bag sealed with black rubber stoppers. 1,1,2 Trichloroethane was found only in the plastic bag samples which were not analyzed soon after collection. In retrospect a number of anomalies and the data might be ascribed to gradual permeation into and out of the plastic bags. Permeation problems should not occur in the stainless steel tanks or in the activated charcoal sample which was stored in a sealed glass container until analysis. In future studies of this kind special precautions should be taken to avoid potential changes in the samples while in storage.

B. Particulate

The Particulate loading and benzene extractable fraction before and during the time of burning are shown in Table 4. The background particulate was high for a rural area and probably due to the slash burning in the

TABLE 4. Particulate loading and percent extractable obtained with high volume samples before and during the broadcast slashburn at Pack Forest, La Grande, Washington, June 24-25, 1968.

Material Number	Collection Period	Particulate	Extractable Percentage
		$\mu g/m^3$	
88	1000 24 June 0923 25 June	64	66.4
73	0900 25 June 1334	160	22.0
87	1334 25 June 1430	1150	30.8
86	1431 25 June 1629	1510	34.2
85	1630 25 June 1827	950	25.4

area on the previous day. This could be due to increased traffic in the area. After ignition, the particulate loading increased to a maximum during the period from 1431 to 1629. This period is equivalent to the second fire stage when the convection column could not support itself against ambient winds. Considerable horizontal smoke drift was experienced. The extractable percentage also increased. Total particulate decreased during third fire stage (1630 to 1827) along with the extractable percentage indicating that the broadcast fire particulate contained a larger amount of benzene soluble matter than the background particulate. For reference, these particulate levels can be compared with those from some of the major cities in the United States in 1961, Table 5.

TABLE 5. Suspended particulate matter, 1961 (Public Health Service, 1966)

City	Particulate	City	Particulate
	$\mu g/m^{-3}$		$\mu g/m^{-3}$
Chicago	190	Cleveland	136
New York City	173	Washington	128
Philadelphia	173	Detroit	118
Milwaukee	146	Dallas	92
Baltimore	142	Seattle	87
St. Louis	141	Atlanta	84
Pittsburgh	137	Miami	54

Plume characteristics from the broadcast fire are shown by aerial soundings in Figure 6 and the data are summarized in Table 6. Location of each of these soundings is shown in Figure 1. The first sounding, 1215, was made during the flight from Seattle to the experiment site. The local industrial pollutants appear to be concentrated in the low level inversion between 1,000 and 2,000 feet.

TABLE 6. Summary of aerial particulate soundings associated with the experimental fire, 25 June 1968. Refer to Figure 2 for location.

Time	Location	Altitude	Particulate			Average Meteorological Range
			Average	Peak	Background	
		μ	$\mu g\ m^{-3}$			km
1215	36 mi. N.E.	152- 488	48	129	30	2.5
1240	over burn	579- 823	60	66	21	2.0
1431	2.4 mi N 72E	914-1584	690	1980	18	0.5
1503	10.6 mi. N 60E	1310-1524	186	216	18	2.3
1530	19.8 mi. N 39E	1524-1768	123	181	12	3.9
1722	17.5 mi. N 18E	244-1555	58	84	3	19.0
1742	25.1 mi. N 4E	457-1494	27	75	3	17.0

The 1240 sounding over the experimental site shows a pronounced inversion between 1,700 and 2,100 feet. When combined with the 1431 sounding, it illustrates existing atmospheric stability.

The 1431, 1503, 1520 and 1530 soundings show the horizontal drift of the smoke plume from the experimental fire. As the convection column rose it broke through the lower inversion reaching a height of 5,000 feet before drifting horizontally. As the plume drifted away from the fire it rose slightly from 5,000 feet to 5,700 feet and appeared to follow the 308 to 390 degree potential temperature surface. The particulate loading associated with two other lower energy fires, consequently lower smoke plume, is shown in the 1742 sounding. The concentration of particulate in the plume diluted downwind. This can be shown as the meteorological range or visibility. Meteorological range is related to particulate loading by:

$$\text{Meteorological range (m)} = 11.7 \times \frac{10^5}{\mu g\ m^{-3}}$$

Visibility increased from 0.5 km in the plume at the fire to 4 km at a distance of 20 km downwind.

The particulate loading was diluted by 2 to 10 fold from the ground site to the horizontal plume at the fire. When this dilution factor is combined with the CO_2 dilution factor from the fire to the ground sampling net of 40 to 80, the results would indicate a total dilution of 80 to 800 from the fire to the top of the convection column.

IV. Summary and Conclusions

Photography, meteorological data, and smoke from an 18-acre broadcast burn of Douglas-fir slash depicted three stages, the buildup, the die-down and

isolated hotspots. Combustion as indicated by CO/CO_2 ratios appeared to be more complete from 850°C flames than from 500°C flames and from stage I than from state II. Concentrations of CO and CO_2 as high as 8,000 and 40,000 ppm, respectively, were found in samples taken from the fire. These gases were diluted to ambient conditions at a height of 5,000 feet in the smoke plume.

Detailed analysis of smoke from the flame area, sampling net, and airplane samples indicated 25 or more different gases and compounds. The number of unsaturated hydrocarbons was small and their concentrations were less than 2 ppm.

Visibility as calculated by the meteorological range increased from 0.5 km in the plume above the fire to 4 km at a distance of 20 km downwind.

LITERATURE CITED

Alquist, N. C. and R. J. Charlson. 1968. Measurement of the Vertical and Horizontal Profile of Aerosol Concentration in Urban Air with the Integrating Nephelometer. Environmental Sci. Tech. 2(5):363-366.

Bell, G. B. and N. E. Waggoner. 1961. A Field Study of Air Pollution in the Lower Sacramento Valley During the 1960 Fall Season. Calif. Dept. Public Health. 66 pp.

Darley, E. F., F. R. Burleson, E. H. Mateer, J. T. Middleton, and V. P. Osterli. 1966. Contribution of Burning of Agricultural Waste to Photochemical Air Pollution. APCA. Jour. 16(12):685-690.

Feldstein, M., S. Duckworth, H. C. Wohlers, and B. Linsky. 1963. The Contribution of the Open Burning of Land Clearing Debris to Air Pollution. Jour. Air Poll. Control Assoc. 13:542-545:546.

Fritschen, L. J., H. Bovee, K. Buettner, R. Charlson, E. Darley, L. Monteith, J. Murphy, and S. Pickford. 1969. The Study of Forest Fire Atmospheric Pollution. Interim Report 68-1, College of Forest Resources, University of Washington.

Pickford, S. R., R. Charlson and K. J. K. Buettner. 1969. A Water-Pump Air Sampler for Use at Remote Sites. Submitted to the Air Pollution Control Association, Pacific Northwest International Section.

List of Figures

Figure 1. Pack Forest and neighboring urban centers. The numbers indicate the location of aerial soundings and samples.

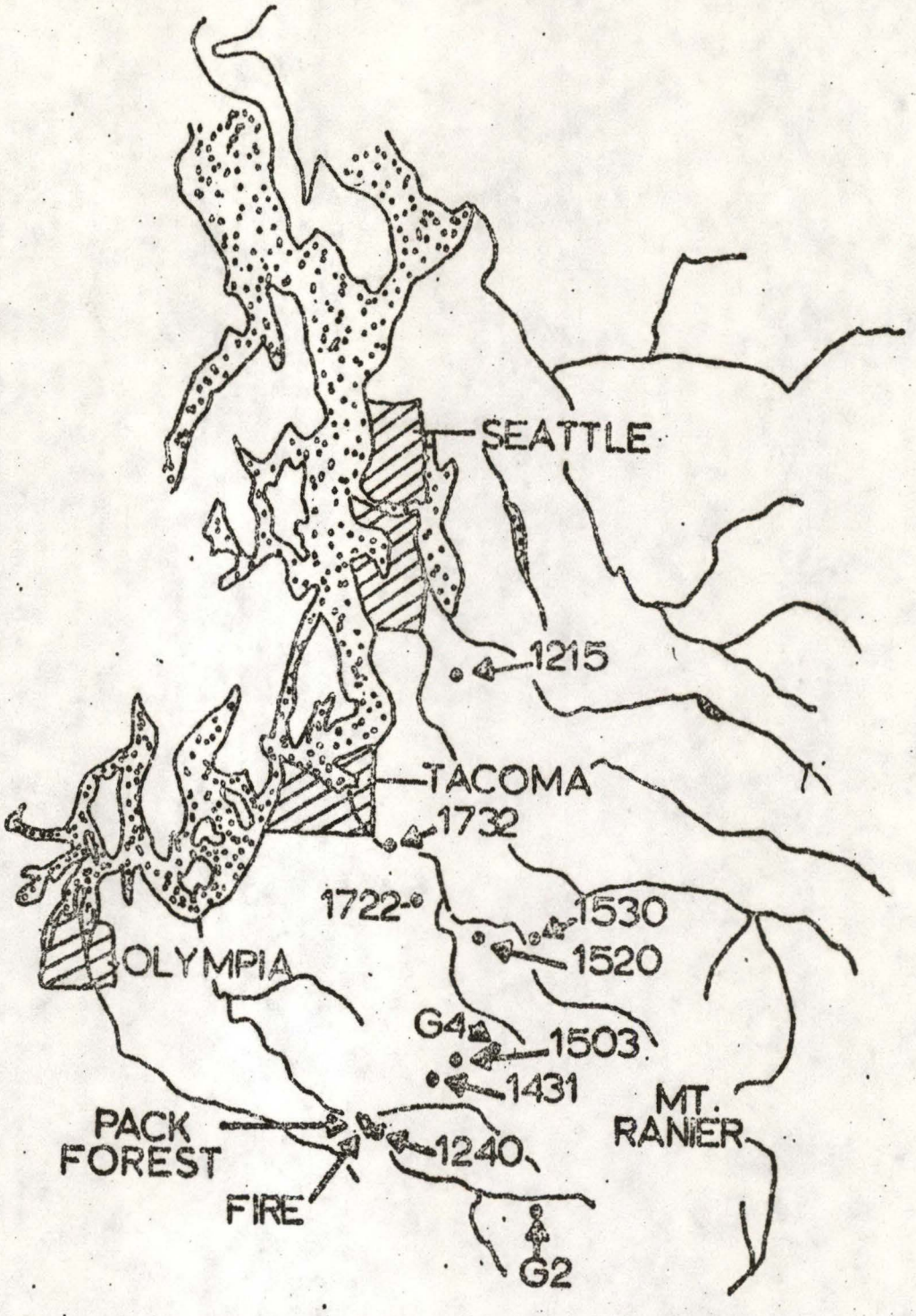
Figure 2. Location of water-displacement air samplers for the June 25, 1968 broadcast burn on Pack Forest.

Figure 3. Horizontal distribution of CO and CO_2 during Period I of the June 25 broadcast burn, Pack Forest, 1968.

Figure 4. Horizontal distribution of CO and CO_2 during Period II of the June 25 broadcast burn, Pack Forest, 1968.

Figure 5. Horizontal distribution of CO and CO_2 during Period III of the June 25 broadcast burn, Pack Forest, 1968.

Figure 6. Mass of suspended particulates and potential temperature observed during vertical soundings of the plume from the June 25 broadcast burn, Pack Forest, 1968.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TACOMA
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RANIER
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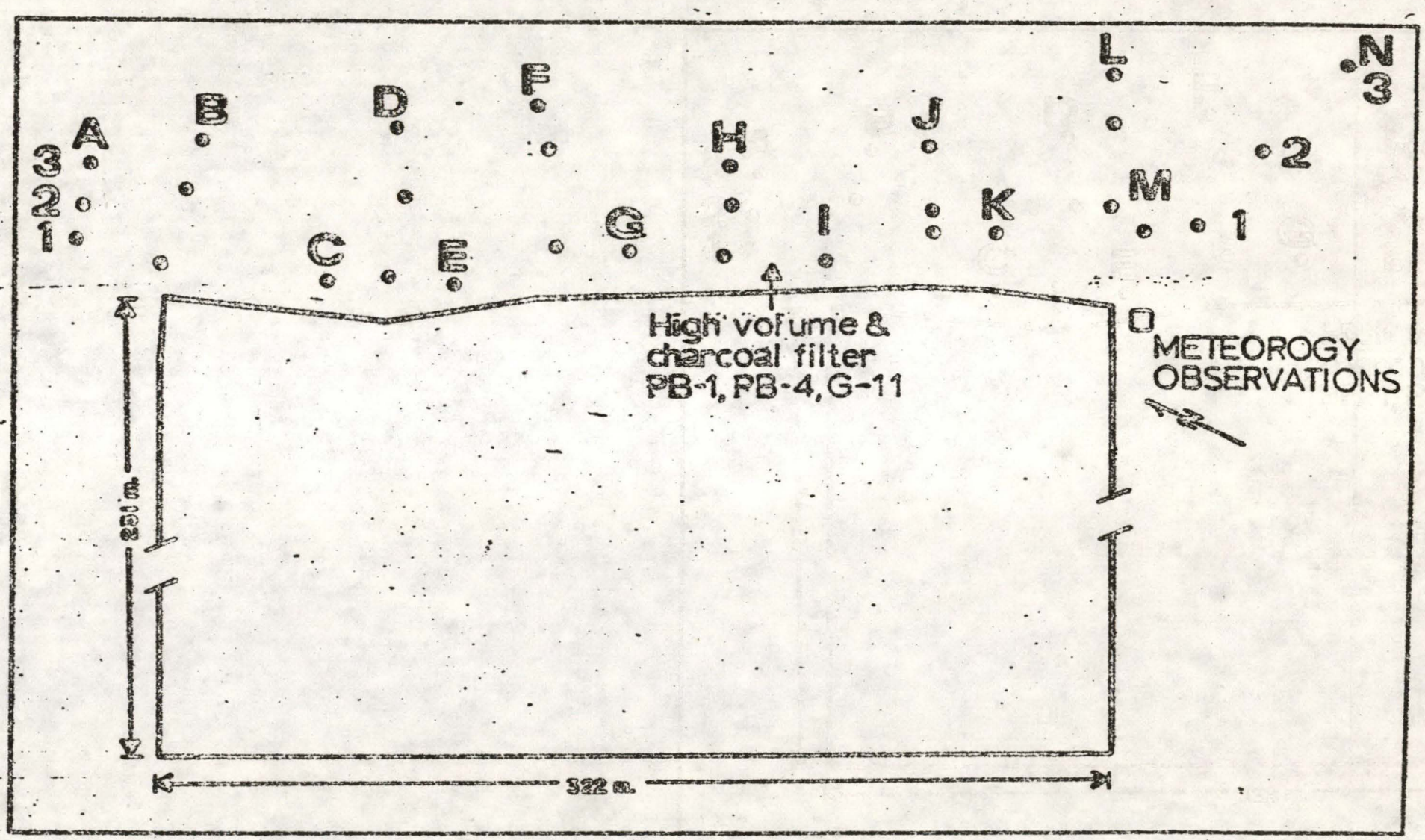
FIRE
G2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OBSERVATIONS
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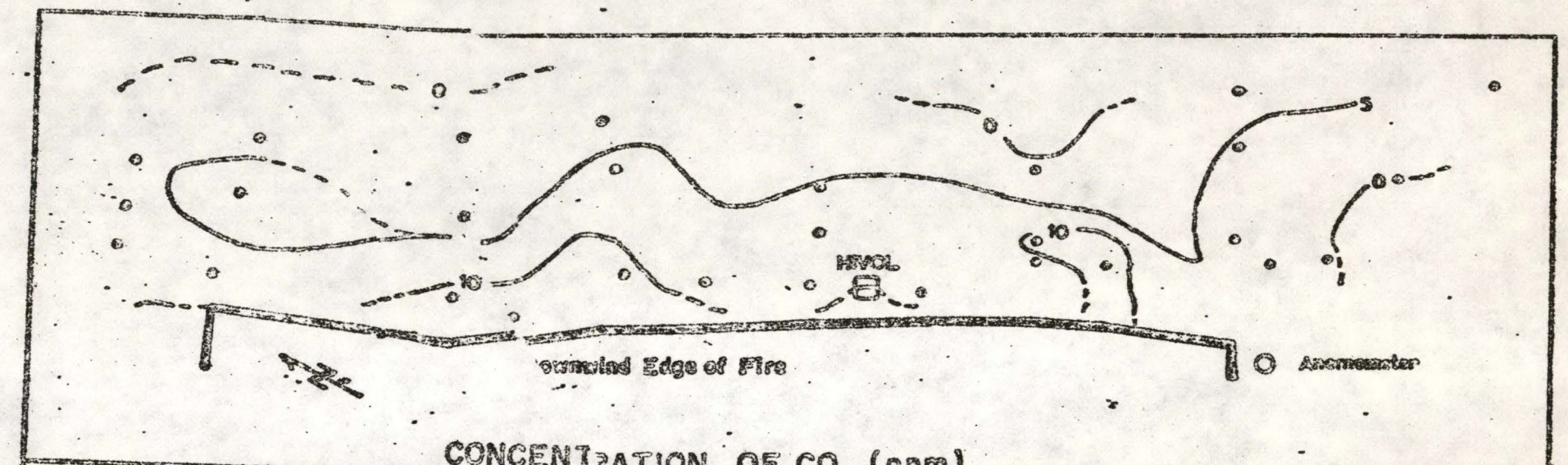
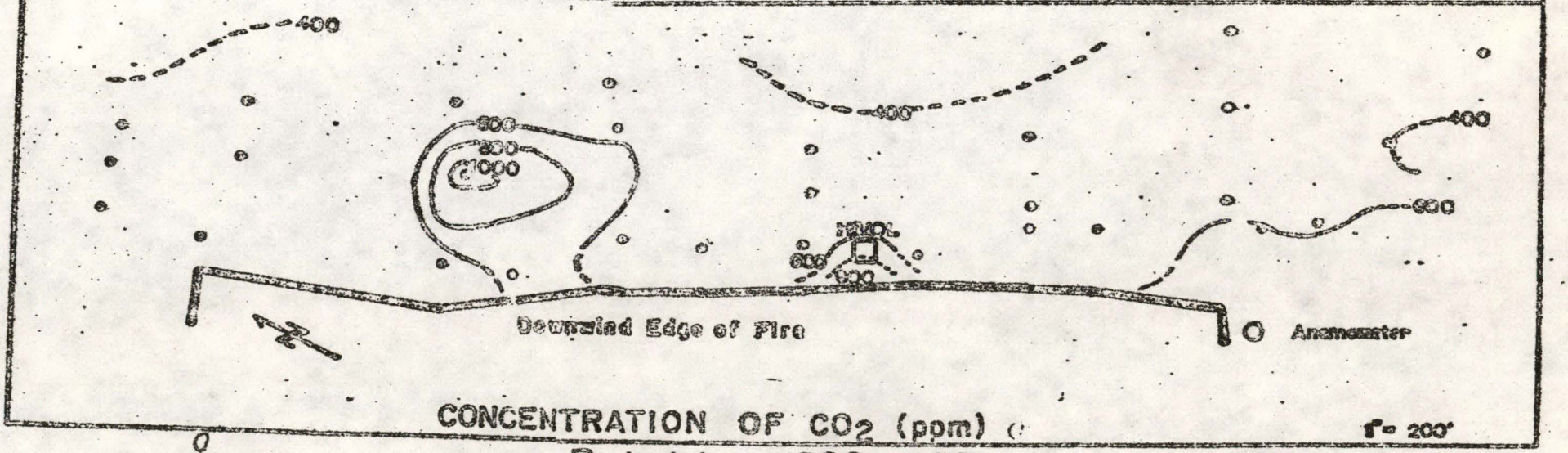


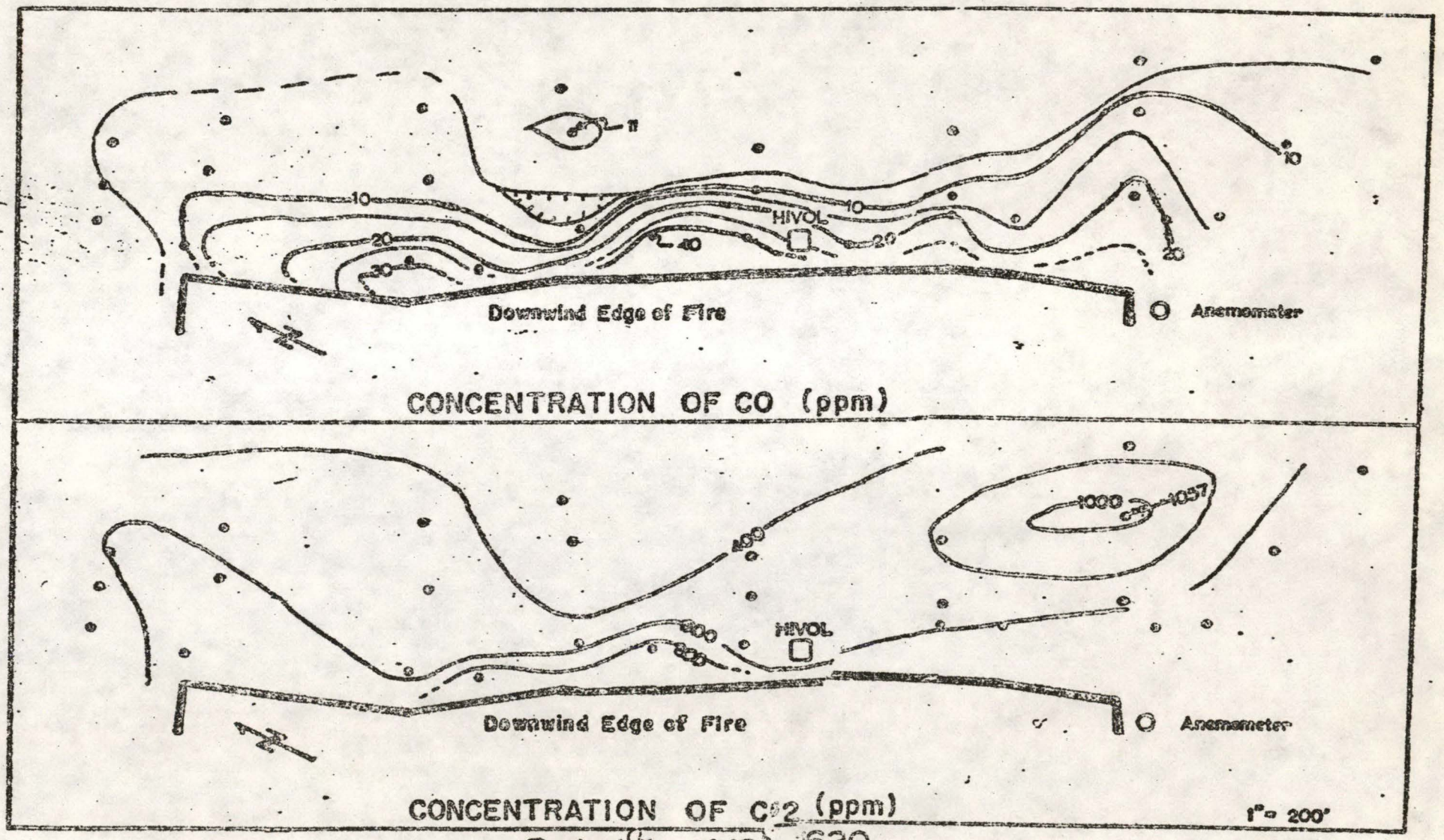
CONCENTRATION OF CO (ppm)



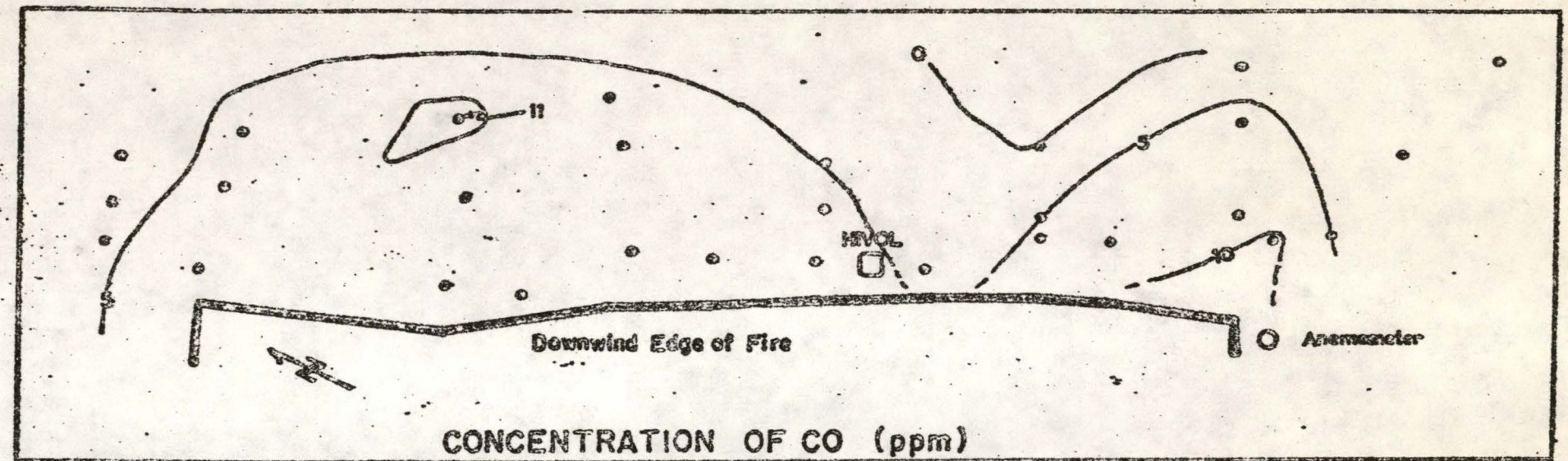
CONCENTRATION OF CO_2 (ppm)

1" = 200'

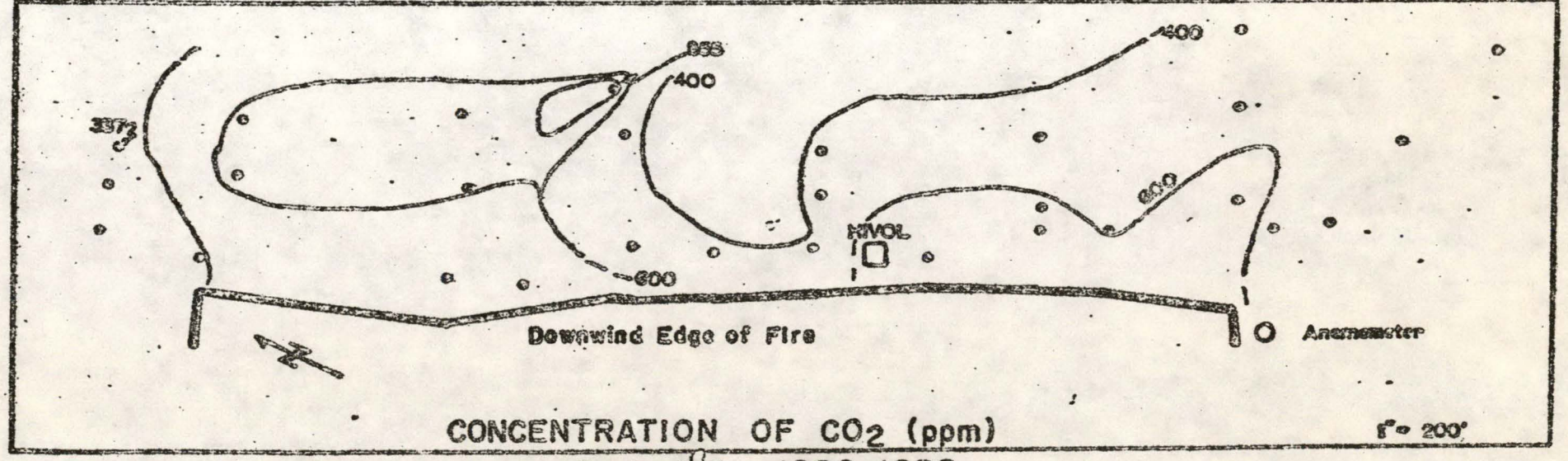
Period 1 1300-1430



Period II 1430 - 1630



CONCENTRATION OF CO (ppm)

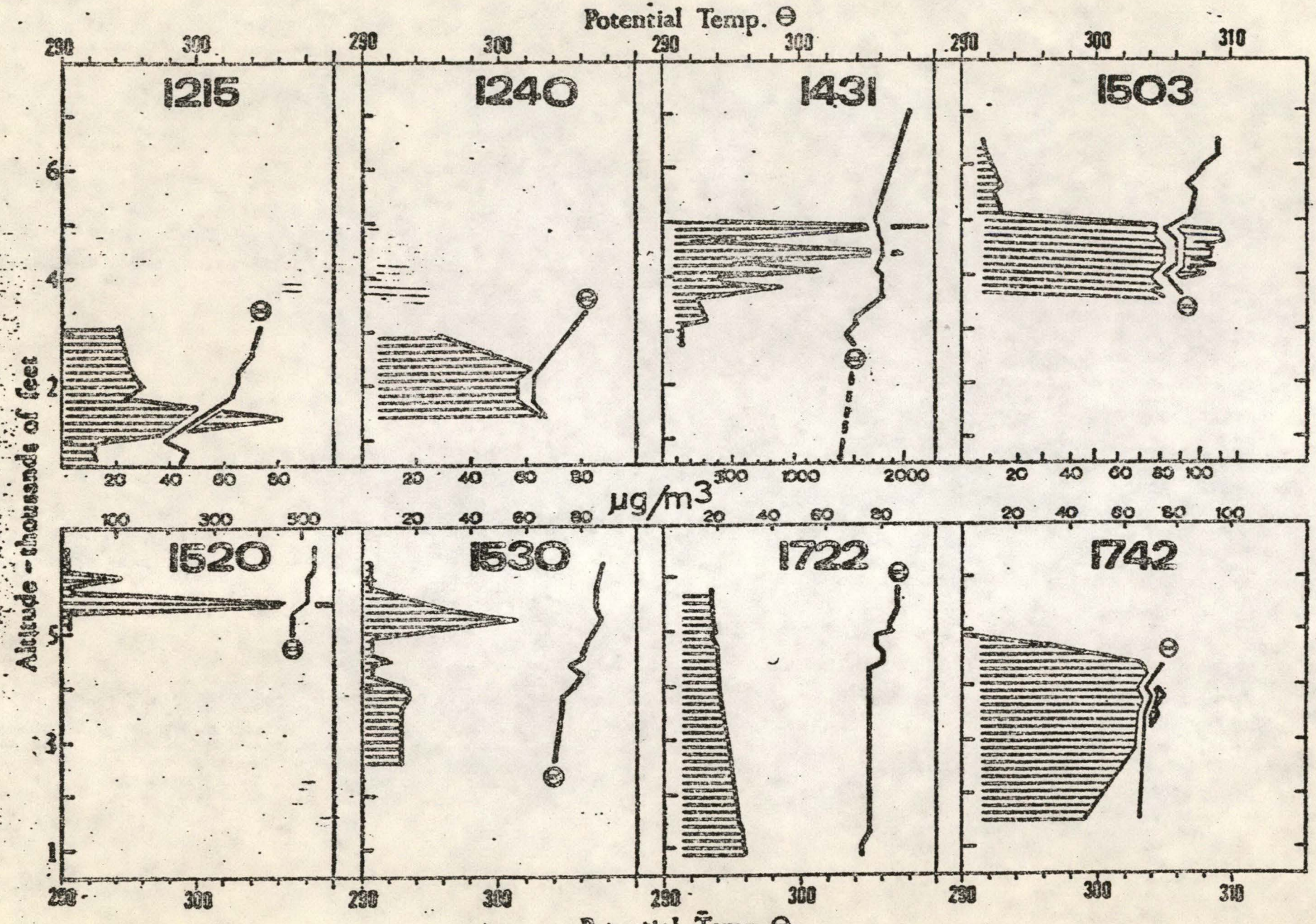


CONCENTRATION OF CO_2 (ppm)

1" = 200'

Period III 1630-1830

fig 5


Potential Temp. Θ
1215
1240
1431
1503
1520
1530
1722
1742
Altitude - thousands of feet
μg/m3